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Orthogonal feedback scheme for network coding

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ABSTRACT

Network coding is a promising technology to improve the throughput and reliability of networks. One critical factor that contributes to a distinct advantage of network coding in a dynamic network circumstance is the existence of a perfect feedback scheme. The current feedback schemes for network coding require special conditions to operate. However, the conditions are extremely hard to meet in practice. In this paper, we propose a novel and effective feedback scheme, orthogonal coded feedback (OCF), in order to avoid the defects of the existing feedback schemes for network coding. Based on our knowledge, this is the first attempt to incorporate orthogonal coding over a finite field into network coding for addressing problems of feedback in network coding diagrams. We establish a simple mathematical model for the feedback scheme, and a thorough analysis has been conducted based on the proposed model. Moreover, we design a simple code generating algorithm for orthogonal coding that can be used in any finite field. Our extensive simulations indicate that the proposed OCF outperforms the current feedback schemes in various network topologies.

1. Introduction

Network coding is a promising technique to improve network throughput and reliability. This technique was discovered by Ahlswede et al. (2000). Since 2000 it has attracted significant research attention. The core of network coding is to encode received data at intermediate nodes between the source and the destination. With the assistance of encoding at intermediate nodes, we can forward, store and encode incoming messages, which is different from the traditional forwarding only operation of an intermediate node.

Feedback scheme for network coding is a critical element for real applications. Jafarisiavoshani et al. (2007a, b) took advantage of feedback to becomes aware of the subspace and discover bottleneck in p2p networks. With the help of perfect feedback, Sundararajan et al. (2008) proposed an extension of the ARQ scheme for network coding, known as *drop-when-seen* algorithm. Similar mechanisms are explored further for use in congestion control and rate adaptation (Ho and Viswanathan, 2009; Eryilmaz and Lun, 2006; Ho et al., 2006). In wireless networks, relay nodes in COPE (Katti et al., 2008) select an optimal packet combination according to reception of the receiver in feedback packets.

However, how to feedback was not discussed in the previous works. Fragouli et al. (2007) tackled this problem for the first time. They used a vector with length N to denote feedback, and set 1 at element i and set 0 for the other elements for the ith receiver. Each intermediate node, upon reception of multiple feedbacks, performs XOR operations on these vectors, and sends the outcome to upstream nodes. Using a number of simple examples, the authors illustrated that feedback can be employed for parameter adaptation to meet QoS requirements as well as for reliability purposes. Moreover, Sundararajan et al. (2009) studied a mechanism that incorporates network coding into TCP . The heart of this mechanism is that receivers acknowledge each degree of freedom in TCP connections. Such a scheme enables a TCP-like sliding-window approach for network coding. Based on the information in feedback, some researchers can get the necessary degrees of freedom, while others can obtain a min-cut set of links in network (Chih-Chun and Xiaojun, 2009) for fast resource allocation. Besides, in wireless mesh network based on Opportunistic Routing (OR), Koutsonikolas et al. (2010) proposed a CCACK scheme, which overcomes drawback null-space-based (NSB) (Joon-Sang et al., 2006) coded feedback and improves both throughput and fairness.

There are some limitations in feedback schemes mentioned above. The *XOR coded feedback* (XCF) scheme, proposed in Fragouli et al. (2007) is the only one that can be used in practice. However, it works just as well in some special network topologies as a result of several limitations. The feedback scheme proposed in Sundararajan et al. (2009) only considers feedback in one TCP connection, and ignores the reception of other TCP connections in the same session. It is able to decrease the times of retransmission in one TCP connection but not in the overall network coding

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session. The feedback solution in Chih-Chun and Xiaojun (2009) is the most complicated one. It not only requires a super node to collect output at intermediate nodes but the super node must possess complete knowledge on the topology of the network. Unfortunately, these two conditions are unavailable in most cases. CCACK in Koutsonikolas et al. (2010) and NSB in Joon-Sang et al. (2006) only consider what should be in feedback packet and do not think about how feedback packet is processed at intermediate nodes. They assume that the belt of forward nodes will send feedback packets upstream. Besides, CCACK is only fit for wireless mesh network based on OR.

In this paper, we propose an innovative feedback mechanism, orthogonal coded feedback scheme which incorporates orthogonal coding into the feedback of network coding. Therefore, it can avoid all of the drawbacks listed above. The information carried by feedback packets will be encoded by an orthogonal code over a finite field. Due to zero correlation between orthogonal codes and linear operations at intermediate nodes, the information in feedback packets will be recovered easily.

Furthermore, a novel simple code generation algorithm for orthogonal codes over a finite field is proposed as the foundation of the OCF scheme. Hadamard transform is unavailable for a large finite field, and its code generation algorithm is very complicated and time-consuming. Therefore, a simple code generation algorithm for orthogonal codes over large finite fields is essential for the OCF scheme to be applied into practice.

We also discuss four basic disciplines on feedback design for network coding. This is a guide to design the feedback algorithm for network coding in practice.

Through OMNet++4.0, a discrete event simulation platform, we develop components and libraries for network coding. The feedback scheme in Sundararajan et al. (2009) only reveals the reception of one TCP connection so that its performance is worse than that of the XCF scheme. The goal of the feedback scheme in Chih-Chun and Xiaojun (2009) is to search for a min-cut set of links in the network and make some impractical assumptions. Therefore, we simulate the XCF scheme and OCF scheme to make comparisons in terms of downloading time and multicasting turn etc. The simulation results demonstrate that the OCF scheme has performed better than the XCF scheme in various network topologies and different packet loss rates.

Our contributions in this paper are listed as follows:

- We propose an OCF scheme which is the first attempt to incorporate orthogonal coding into the feedback of network coding.
- We proposed a novel simple code generation algorithm for orthogonal codes over any large finite field to advance the OCF scheme in practice.
- We summarized the principles of a feedback system design for network coding. It is the first time for network coding to explore the basic framework of feedback thoroughly.

The remainder of this paper is organized as follows. We introduce XCF scheme in Section 2 and system modeling in Section 3. We then outline a number of examples, illustrating the problems of previous feedback schemes in Section 4. Several disciplines on feedback systems for network coding are summarized in Section 5. In Section 6, we discuss the OCF mechanism. Extensive simulations are performed and presented in Section 7. Finally, we conclude the paper in Section 8.

2. Related work

Fragouli et al. (2007) examined possible ways of feedback in the context of systems that employ network coding. They investigated several questions: (1) how does feedback help? (2) how should feedbacks be designed?, and (3) how could feedback be analyzed at the end source? We summarize their conclusions as follows.

2.1. Benefits of feedback for network coding

Current network systems and protocols use feedback, e.g. TCP ACK, from receivers and senders against packet loss and congestion control. Feedback of network coding can also achieve these goals.

If feedback is appropriately designed, it can help systems with network coding to improve reliability. For a network which suffers packet erasures, the ARQ and FEC are the major remedies for this problem. Through discussion about the schemes improving reliability in Fragouli et al. (2007), the authors discovered that the schemes using ARQ have better performance on the overall delay than using FEC. On the other hand, feedback is the foundation of ARQ that needs to know the reception of packets implied by feedback. Therefore, based on perfect feedback, a solution improving reliability for a network coding system can be designed.

Feedback can also be used to adapt network coding parameters for various network traffics in terms of QoS requirements. In implementations of network coding, the transmitted data is divided into fixed-size generations, and each generation is further divided into blocks. Intermediate nodes linearly combine blocks in the same generation (Maymounkov et al., 2006). From previous research (Fragouli et al., 2008), we can see that the size of generation has influence on multicast capacity and affects the achievable rate that receivers observe. It also determines the delay for original data decoding. Without feedback, the source has no idea on the reception of packets and in general has to select the strategy that will maximize the achievable throughput with high probability even though it may decrease the achievable rate and delay the decoding. There is a concrete example showing this in Fragouli et al. (2007). In a word, the feedback from the receivers to the source can help the system that deploys network coding to adjust to the generation size, improve the achievable rate, and thus, decrease the decoding delay for delay sensitive applications.

2.2. Information in feedback for network coding

Consider a network with a single source and multiple receivers. Intermediate nodes process coded packets with random network coding (RNC) (Ho et al., 2003) operation. Receiver collects N coded packets $Y_1, Y_2, \ldots, Y_N$ for one transmission generation in which source sends n packets $X_1, X_2, \ldots, X_n$ downstream. We say that the ith receiver at time t collects a subspace Π_i, where Π_i is the vector space spanned by the coding vectors in coded packets which receiver i has received up to time t. If this receiver has k linearly independent coding vector in possession at time t, then we say that $\dim(\prod_i) = k$. If a coded packet is innovative to this receiver, or in other word the associate coding vector in packet does not belong to Π_i, it will increase the $\dim(\prod_i)$ by one. As long as $\dim(\prod_i) = \dim(X) = n$, the receiver i has collected a basis of the n-dimensional space and can decode the original data. Therefore, regardless of the reception of a packet, if only $\dim(\prod_i) = \dim(X) = n$, we know that transimission for the current generation is complete and packets of the next generation will begin to be sent. So, the information in feedback which the source wants to know is $\dim(\prod_i)$. In this paper, let $D_i = \dim(\prod_i)$ denote the degree of freedom for one generation owned by receiver R_i.